EFFECT OF H_2 PRODUCED THROUGH STEAM-METHANE REFORMING ON CHP PLANT EFFICIENCY

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ABSTRACT

In-situ hydrogen production is carried out by a catalytic reformer kit set up into exhaust gases for a CHP plant based on spark ignition engine running under lean conditions. An overall auto-thermal reforming process is achieved. Hydrogen production is mainly dependent on O_2 content in exhaust gases. Experiments are conducted at constant speed at 2 air/fuel ratios and 4 additional natural gas flow rates. H_2 content varies in the range 6% to 10% in vol. H_2 content effect is analyzed with respect to performance and emissions. Comparing with EGR shows an increasing of electrical efficiency of 1% whilst heat recovery decreases by 1%. NO and HC decrease by 18% and 12%, but CO increases by 14%, respectively. The results show that: (i) graphite joints were destroyed under effect of H_2 and high temperature; (ii) a cold spot appeared in the RGR line, and condensation has as consequence a carbon deposit; and (iii) no back-fire or knock occurred.

Keywords: Hydrogen, CHP, natural gas, power, efficiency, environmental impact.

1. INTRODUCTION

Before switching to a hydrogen-based economy, transitional solutions are necessary. Hydrogen and natural gas blend is considered a contemporary idea using the natural gas existing networks (without additional investment). In 2010, at an international conference on hydrogen production, Yildirim [1] presented the NaturalHy project of European Union. One of the major objectives of their project was to define the conditions under which hydrogen can be blended with natural gas for final users using natural gas networks. Amongst the

final uses, Combined Heat and Power (CHP) plants are the prime movers with the best efficiencies, see Orlando [2]. Small or medium CHP plants use internal combustion engine.

The potential benefits of using H_2 in spark ignition (SI) engines may be listed as follows, see Bauer and Forest [4]:

- Operating conditions can be very lean, wherein the fuel equivalence ratio, ϕ, can reach a limit of 0.1. Natural gas and gasoline have lean limits of 0.53 and 0.7, respectively.
- The laminar flame speed for a stoichiometric hydrogen/air mixture (at 2.65-3.25 m/s) is about seven times higher than for methane or gasoline. This property of hydrogen leads to a very fast rate of heat release and a decrease of the wall heat transfer ranging from 17% to 25% of the primary fuel energy for hydrogen, compared to 22% to 33% for natural gas or 30% to 42% for gasoline.
- The auto-ignition temperature is about 860 K for a stoichiometric mixture with air, while it is 810 K for methane and 750 K for gasoline at standard pressure (1 atm). This property then increases the compression ratio and the thermal efficiency up to 30%, respectively.
- The “quenching distance” is defined as the distance from the cylinder wall from which the flame quenches due to heat losses. It characterizes the flame quenching property of a fuel in internal combustion engines. The quenching distance of hydrogen (0.064 cm in standard conditions) is approximately 3 times lower than that of other fuels, such as gasoline (0.2 cm in standard conditions) or methane (0.203 cm in standard conditions).
- Emissions from hydrogen fuelled engines are neither toxic nor photochemical reactive.

Karim [3] has identified two major risks due to the combustion of H_2/natural gas blends in spark-ignition engines. The first one is called “back-fired” and can appear from a hot spot in inlet line. The second one is the well known “knock” for spark ignition engine.

Some previous studies [4-20] have then tested the effect of natural gas - hydrogen mixtures in spark ignition engines (see Table 1). Their measured performances have showed that electric power output is improved by engines fuelled with mixtures of natural gas/H_2 compared to natural gas only fuelled engines. However, a similar conclusion on emissions (CO, HC and NOx) cannot be drawn up. Li and Karim [21] resumed their literature survey about engines fuelled by H_2 (pure or blended) as: “Experimental results are not in good agreement since engine and operational conditions are different”.

In 1981, an onboard hydrogen production from methanol is described by Sjostrom *et al.* [22]. Steam methane reforming (SMR) in exhaust gas recirculation over Ni-catalyst is detailed as its concept is schematically shown in Figure 1. Hydrogen properties help run engine in leaner conditions than pure gasoline. Higher efficiency and lower pollutant emissions are investigated as well.

Particulate matters from diesel engines are subjected to stringent regulations. Because of both significant amount of oxygen and available "free" heat in exhaust gas, onboard catalysis is detailed for those applications, see Zheng *et al.* [23]. H_2 and CO are products over catalysts and in-cylinder premixed combustion is expected. Zheng *et al.* explained combustion is similar to dual combustion in these operating conditions. Tsolakis and Megaritis [24] tested diesel/biodiesel blends in these conditions. Afterwards, they have extensively published results in papers [25-26].

Initially bound to compression ignition engines (ex: diesel/biodiesel), reforming of combustible gases (example, steam methane reforming (SMR)) is a catalytic process used to produce hydrogen through the following chemical reactions:

Steam reforming (endothermic reaction):	$CH_4 + H_2O \rightarrow 3H_2 + CO$	(1)
Auto-thermal reforming:	$CH_4 + ½O_2 + H_2O \rightarrow CO_2 + 3H_2$	(2)
Water-gas shift reaction (exothermic):	$CO + H_2O \rightarrow H_2 + CO_2$	(3)
« Dry » reforming (exothermic):	$CH_4 + CO_2 \rightarrow 2CO + 2H_2$	(4)
Partial oxydation (exothermic):	$CH_4 + ½O_2 \rightarrow CO + 2H_2$	(5)

SMR uses only the first equation (production of hydrogen through hydrocarbon cracking by water vapour and temperature). In order to bring water vapour, oxygen and carbon dioxide together with the temperature needed to activate these reactions for the hydrogen production, the exhaust gases of CHP power plants can be used. The principle of the reforming process is outlined in Figure 1.

In order not to decrease the thermal efficiency because of the endothermic steam reforming reaction (equation 1), combining three reactions (equations 2-5) can lead to a global auto-thermal reforming process (tri-reforming of natural gas).

Exhaust gas composition of CHP gas engines (operating in lean burn conditions) are favorable for the activation of these reactions above:

- Presence of CO_2 (equation 4),
- Lean burn operating conditions: presence of O_2 (equation 2 and 5),
- Significant water vapor content for steam reforming: H_2O (equation 1 and 3),
- High temperature (> 340°C) for the activation of the reactions.

These reactions have been produced through a catalyst, formerly used for the oxidation of carbon monoxide and unburnt hydrocarbons produced from the incomplete combustion in gas engines. The concept is built on a triple idea as shown in Figure 1:

1. Plunge the catalytic reforming device into the gas exhausts in order to keep it at high temperature,
2. Take part of the gas exhaust in order to feed the catalyst with the water vapor, the oxygen and the carbon dioxide contained in the exhaust gases,
3. Supply the intake air and gas line with the reformed gases (among which hydrogen) following the example of Exhaust Gas Recirculation (EGR) used in the car industry for reducing NOx of diesel engines.

Such an application, natural gas HCCI engine operation with exhaust gas fuel reforming, was studied by Yap *et al.* [27]. In this configuration, they obtained an extension of the HCCI lower load boundary for a given intake temperature.

As yet, H_2 or NG-H_2 gas network for distributed applications does not exist. Therefore, in-situ H_2 production and consumption become a valuable solution, especially for CHP engines operating under lean conditions, for testing their operational behaviour. CHP applications using engines are lesser constraint in terms of weight, space (volume), and have a lower compression ratio than those in automotive applications. More over, those applications run at fixed load (usually full load). Then, such applications can be favourably considered. More over, in the NATURALHY context [1], it seems important to report a know-how on such application but it is not possible to feed engine from H_2 cylinders for cost and safety reasons.

This paper deals with the performances of a reforming device in the gas recirculation line of a CHP gas engine. The reforming device is composed of a catalyst bed where part of the exhaust and part of the natural gas flow react. First test bench, including its instrumentation, is described in the following section. The effects of natural

gas flow rate for two engine operating conditions at fixed 5% (in vol.) on the performance are studied in the following cases:

- At low frequency: H_2 production, electric efficiency, exhaust gas emissions, temperature aspects
- At high frequency: in-cylinder pressure
- Comparison between EGR and RGR (Reformed Gas Recirculation) results

Finally, the operational difficulties encountered during tests are explained in detail.

2. MATERIAL AND METHODS

The test bench is a spark ignition (SI) engine fuelled by natural gas. This installation is a combined heat and power plant operating at a fixed engine speed, as specified in Table 2.

Catalysts are based on noble metals. In the past studies, numerous handmade catalysts (Ni/Al_2O_3 and $NiMgOAl_2O_3$) and commercial products from DCL© and Jonhson-Matthey© (KATALCO series, and CRG-LHR) were considered. After specific tests, DCL© product was selected because of its high performance in converting methane into hydrogen. Figure 2 describes the reforming device that was used in experiments. The main exhaust gas stream surrounds the catalyst bed in order to maintain the catalyst at the minimum desired temperature.

The test bench is equipped with two types of experimental sensors. The first ones correspond to low frequency measurements (1 Hz):

- Catalyst inlet and outlet temperatures and catalyst housing inlet and outlet temperature for exhaust gases: K-type thermometer, calibration was made by even in an electric furnace for 5 specific temperatures, and error was found to be less than 0.5 °C.
- Mass flow meter of main natural gas SI engine feed line (0-1200 Nm^3/h): El-flow® from Bronkhorst®, calibration was done in measurement range, and the error was found to be less than 1%
- Mass flow meter of the additional natural gas at the catalyst inlet (0-600 Nm^3/h): El-flow® from Bronkhorst® associated with a valve Metso automation B1CU11/40 (600°C, 8 BAR), calibration was done in measurement range, and the error was found to be less than 0.5%.
- Mass flow meter of the intake air (0-1500 kg/h): ABB® sensyflow VTS, calibration was done in measurement range, and the error was found to be less than 1.0%.

- Two gas analysers (on dry basis), and the error was found to be less than 0.5% on full-scale
    - Engine exhaust gases were analysed with
        - HORIBA® VA300 analyser : O_2 (0-25%), CO_2 (0-20%) CO (0-1%), NO (0-2000 ppm) and
        - COSMA® Cristal 500 analyser : HC (0-5000 ppm)
    - Catalyst outlet gases were analysed with
        - ROSEMOUNT® NGA2000 : H_2 (0-30%), O_2 (0-30%), CH_4 (0-30%), CO (0-30%), CO_2 (0-30%) and
        - SIEMENS® H3-600 : CO_2 (0-16%)

  Before each test, the reference gas from cylinder was measured, and the calibration was adjusted as required. In the same way, natural gas composition was measured by gas chromatography. This was required for low heating value (LHV).
- Wattmeter, ENERNIUM-CFG1
- Water cooling flow rate of SI engine (0-50m^3/h): Pitot probes (the error was found to be less than 0.5%)
- Temperature at different point of water cooling circuit of the engine (PT100, 0-200°C): 12 measured points, calibrated by the same procedure as K-type thermometer.

A Labview interface was used with the data acquisition system from National Instrument®:

- Rugged, compact 12-slot chassis to house any SCXI modules
- USB Data Acquisition and Control Module
- 32-Channel Thermocouple/Voltage Input Module
- Isothermal construction minimizes errors caused by thermal gradients
- 32-Channel, ±10 V Analog Input Module
- SCXI-1300 Low-Voltage Screw Terminal Block

The second ones correspond to high frequency measurements (90 kHz):

- AVL® QH32D sensor, gain 25.28pC/bar Range 0-200bar
- a Piezo Amplifier AVL 3066A01, gain 400pC/V with no reference of pressure
- a Druck type PTX 510 – Range 2.5 bara inside inlet manifold to give the reference of pressure.

In-cylinder pressure diagram is recorded and averaged over 100 consecutive cycles because of cycle-to-cycle variations.

Experiments were conducted on the operating conditions of engine speed of 1500 RPM, Spark Advance 14 CA BTDC. Two air fuel ratios (AFRs) are studied as 1.4 and 1.6. The electric load is firstly chosen. Consequently, main natural gas mass flow rate is obtained by the engine actuator. Then, additional natural gas flow is manually fixed in EGR line and chosen to get H_2 production. Indeed, engine actuator drives itself the main natural gas flow rate. An iterative procedure is required to maintain AFR at the fixed value. A part of natural gas is not converted. This is not a disadvantage of the system since the main natural gas flow rate is decreased as much.

For safety reasons, the following conditions were restricted:

- Operation at 80% of nominal electric power output
- Some part of additional natural gas flow rate over catalyst does not react. That is to say, oxygen is completely consumed at catalyst outlet.

The calculations involve averaging the data over a period of 15 minutes in a steady state form. The H_2-enhanced engine electrical efficiency η_e is defined as follows:

$$\eta_{elec} = \frac{W_{elec}}{LHV\,(q_{NG} + q_{NGR})} \tag{6}$$

where q_{NG} the natural gas flow rate (main stream), q_{NGR} the natural gas flow rate to reform and LHV the low heating value as seen in Figure 1. Considering from the law of uncertainty propagation [28], the relative uncertainty of η_{elec} in Eq. (2) and $u(\eta_{elec})/\eta_{elec}$ are determined as follows (as long as the variables $W_{elec}, LHV, q_{NG}, q_{NGR}$ are not correlated):

$$\frac{u(\eta_{elec})}{\eta_{elec}} = \left(\left(\frac{u(W_{elec})}{W_{elec}} \right)^2 + \left(\frac{u(LHV)}{LHV} \right)^2 + \left(\frac{u(q_{NG})}{q_{NG}} \right)^2 + \left(\frac{u(q_{NGR})}{q_{NGR}} \right)^2 \right)^{0.5}$$ then η_{elec} error becomes about 0.5%.

In this CHP plant, heat recovery comes from intercooler (after inlet air compressor), motor unit (oil and water jacket) and exhaust gas heat exchanger. Heat recovery (*HR*) is transferred by plate heat exchanger to the final use.

$HR = q_w \, c_p \left(T_{fu}^o - T_{fu}^i \right)$ with an error about 0.5%.

3. RESULTS AND DISCUSSION

Experimental results are presented considering two important parameters. Activation of chemical reactions within the catalyst needs natural gas, steam and/or O_2. Since exhaust gas analysis is on a dry basis, water vapour was not measured. Therefore, all results shown in Figures 4 and 5 are presented according to the NGR (natural gas to reform) over O_2 ratio in engine exhaust gases. Two O_2 contents were tested: 7% and 8% in the engine exhaust gases.

3.1 Results at low frequency

Figure 4 shows the composition of the reformed gases (RGR) at the catalyst outlet. Production of H_2 is about 10% in volume which appears to be low (compared to other processes for H_2 production) due to the high content of N_2 within the reformed gases. Production of H_2 depends on O_2 content in exhaust gases and increasing O_2 content increases H_2 production. However, production of H_2 decreases with NGR/O_2 ratio. This ratio is essentially determined from natural gas flow rate at catalyst inlet and O_2 content in exhaust gases. The results are proposed for two different O_2 values. Thus, NG flow rate varies for each set only. Increasing NG flow rate at the catalyst inlet decreases H_2 production. This observation must be balanced with the fact that unconverted NG still remains at the catalyst outlet. Whatever O_2 value in exhaust gas is, unconverted NG only depends on the NGR/O_2 ratio in a consistent way.

For safety reasons, experiments were limited at a NGR/O_2 ratio of about 1.5 (in order to avoid O_2 presence at the catalyst outlet). Production of CO proves that steam reforming reaction is not the predominant one within the catalyst. Partial oxidation reaction must not be neglected. Productions of CO and H_2 are comparable. CO_2 content at the catalyst outlet depends on its initial value (at the catalyst housing inlet) and CO_2 production within the catalyst. Production of CO has different consequences in SI engines from fuel cells.

Catalyst and catalyst housing inlet/outlet temperatures are plotted in Figure 5. Catalyst inlet temperature corresponds to the engine turbine outlet (assuming heat losses are neglected, see Figure 1). We can see that O_2 in exhausts has little influence on in-cylinder combustion. Catalyst inlet temperature is higher at 7% O_2 than 8% O_2, as expected. Catalyst outlet temperature gives information that reactions are exothermic: at

a catalyst inlet temperature around 370°C, the catalyst outlet temperature reaches 610°C. This is a direct confirmation of production of CO. The greater the O_2 content at the inlet is, the hotter the catalyst outlet temperature is. At the catalyst housing outlet, temperature is more or less constant since EGR is 5% (in vol.). The differences observed on catalyst housing temperatures, at 7% and 8% O_2, are assumed to be due to the combustion process.

Electric efficiency and thermal recovery are plotted in Figure 6. This plot has H_2 content as x-axis. The following observations can be obtained from this figure:

- Higher the O_2 content in engine exhaust, lesser the electric efficiency is found.
- Higher the H_2 content, greater the electric efficiency is obtained. This observation is more sensible with high O_2 content (or H_2 production)
- Similar comments could be pointed out for heat recovery. However, some differences can be discussed here:
    - At 7% O_2 in the engine exhausts, electric efficiency increases slightly and heat recovery increases significantly.
    - At 8% O_2 in the engine exhausts, electric efficiency increases significantly and heat recovery slightly.
    - This observation is attributed to the specific physical properties of hydrogen. Operating at a significant O_2 value reduces in-cylinder flame speed. Production of H_2 may compensate this effect.

The composition of the engine exhaust gases is plotted in Figure 7. Emissions of unburnt hydrocarbon HC are greater at 8% O_2 than 7% O_2. Engines lean operating conditions reduce in-cylinder flame speed and increase unburned hydrocarbon emissions. However, hydrogen H_2 has a beneficial effect since HC emissions decrease at high H_2 rate. Emissions of CO (in the engine exhaust gases) are around 530 ppm. H_2 addition into the engine increases moderately that value. Emissions of CO_2 depend mainly from the engine operating conditions. H_2 addition has no significant effect. Emissions of NO are lower at 8% O_2 than 7% O_2, as expected. With 7% O_2, emissions of NO become greater at higher H_2 addition rate. Nevertheless, at 8% O_2, emissions of NO seem to be constant whatever H_2 rate. As given in Table 1, there is no agreement between results obtained by various researchers. This may be due to inconsistent engine operating conditions.

3.2 Results at high frequency

At 7% O_2, two important features of in-cylinder diagram history must be highlighted. Ignition delay is the delay between spark timing and an effective heat release rate. The greater the H_2 addition, the higher the peak pressure is observed. The reason is attributed to the physical properties of H_2 as reported in the introduction section. At 8% O_2, same comments could be made. Nevertheless, the leaner the operating conditions are, the lower the electric efficiency is, and the smaller the H_2 effects are.

3.3 EGR – RGR comparisons

Since CHP plant performances vary, in particular, with atmospheric conditions, measurements with and without the reforming device were carried out the same day under the same conditions. Such comparative results are presented in Table 3.

For 5% EGR, electric efficiency increases by 0.3 and heat recovery decreases by 1.0 (absolute basis). In the reference cases (by-pass of the reforming device), 60.7% of heat release during combustion is recovered. Using the reforming device resulted in a better conversion, due to H_2 addition, of the mechanical work (high quality) than heat (low quality).

A decrease in the emissions of unburnt hydrocarbons is observed as well. This could probably be due to a smaller hydrogen extinction flame limit than hydrocarbons.. That property may explain the lower hydrogen rates measured under RGR. CO emissions show an increase (probably) due to high level of CO in the RGR line (compared to traces in the EGR configuration). The reason for the decrease in NO emissions is not trivial and further investigation must be carried out.

4. OPERATIONAL FEEDBACK

Two major difficulties were observed:

1. Graphite joints, LATTYGRAF EFA, 2 mm, for high temperature, were chosen. Nevertheless, under combined effect of H2 and high temperature, joints were destroyed. Figure 9 shows reformer kit in 3D. On the left, the first design was assembled with coupling sleeves. In this design, “honeycomb” catalyst remained accessible for maintenance inspection. On the right, the second design is welded. No inspection is then possible.

2. Downstream, the reforming device outlet (RGR line) was set up with a heat exchanger in order to recover the excess heat from the exothermic reactions. A cold spot appeared in the RGR line and water from condensation together with carbon deposit were collected, see photo in Fig 10.

Tests were conducted over a period of 5 months (September to March). Neither bach fire nor knock were encountered.

5. CONCLUSIONS

In this paper, the effect of H_2 in-situ production has been investigated on the engine performance as fuelled by natural gas. The H_2 production concept has provided additional benefits, namely, “using the heat recovered from exhaust gases to initiate reforming process and moist exhaust gas recirculation at no additional cost”.

Experiments are conducted at 80% of full load. Two engine operations are studied (7% and 8% O_2 in exhaust gases). The reformed gases at the catalyst outlet contain H2 (8 to 15 % in vol. on dry basis), CO (3 to 6 % in vol.), CO_2 (9 to 10 % in vol.), unconverted natural gas (2 to 12 % in vol.) and N_2 (the complement). Unconverted natural gas is considered as a safe operation condition.

Chemical reaction is overall exothermic. The reformer exit temperature raises up to 620°C in regards to its inlet temperature at 350°C. This observation does not depend on the engine operation at lean condition (7% or 8 % O_2 in exhaust gases). The reformer exhaust gases temperature (main stream) is not constant.

Engine efficiency shows an increase for either electric efficiency or thermal recovery according lean condition of engine operation.

In-cylinder pressure data acquisition is at high frequency. The greater the H_2 content, the higher the peak pressure is observed.

Some operational difficulties are reported as: (i) In the first design, “honeycomb” catalyst remained accessible for maintenance inspection. Joints were destroyed under combined effect of H_2 and high temperature. The second design is welded. (ii) A cold spot exists in RGR line and carbon deposit is collected with condensation.

Furthermore, in-situ H_2 production requires further investigation especially to improve H_2 production and efficiency. Retrofitting CHP plants with spark ignition engines can easily be done for potential applications.

NOMENCLATURE

ABDC	after bottom dead center	(CA)
ATDC	after top dead center	(CA)
BBDC	before bottom dead center	(CA)
BTDC	before top dead center	(CA)
CA	crank angle	(CA)
HR	heat recovery	(W)
LHV	low heating value	(J kg^{-1})
q	mass flow rate	(kg s^{-1})
T	temperature	(K)
W_{elec}	electrical power	(W)

Greek letters

η_{elec}	electrical efficiency

Superscripts

i	input
o	output

Abbreviations

CHP	Combined Heat and Power
EGR	Exhaust Gas Reciculation
HCCI	Homogeneous Charge Compression Ignition
NG	Natural Gas
NGR	Natural Gas
RGR	Reformed Gas Recirculation
RPM	Rounds per minute
SI	Spark Ignition to Reform
SMR	Steam Methane Reforming
Fu	final use

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Figure 1

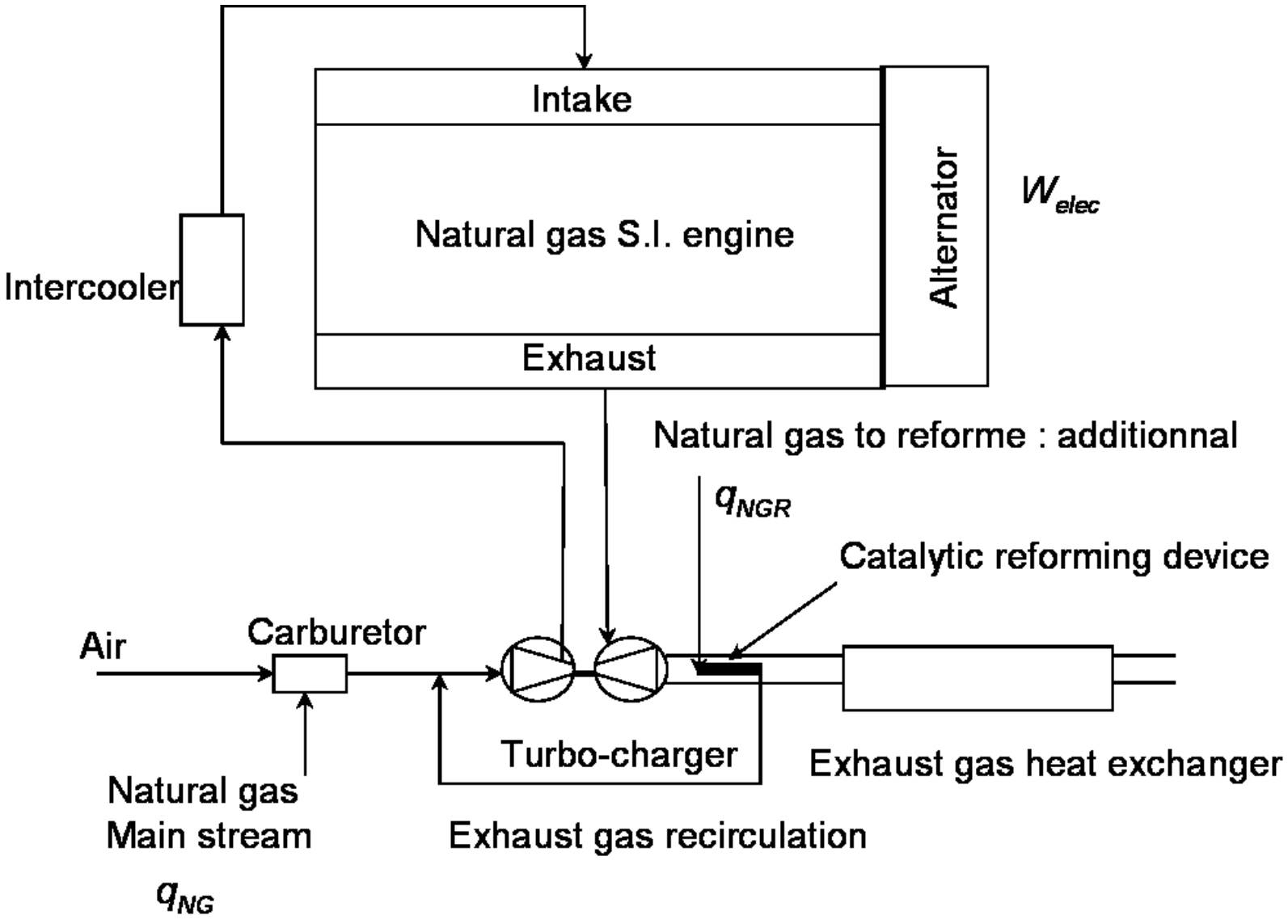

Intake
Natural gas S.I. engine
Exhaust
Alternator
W_{elec}
Intercooler
Natural gas to reforme : additionnal
q_{NGR}
Catalytic reforming device
Air
Carburetor
Turbo-charger
Exhaust gas heat exchanger
Natural gas
Main stream
q_{NG}
Exhaust gas recirculation

Figure 2

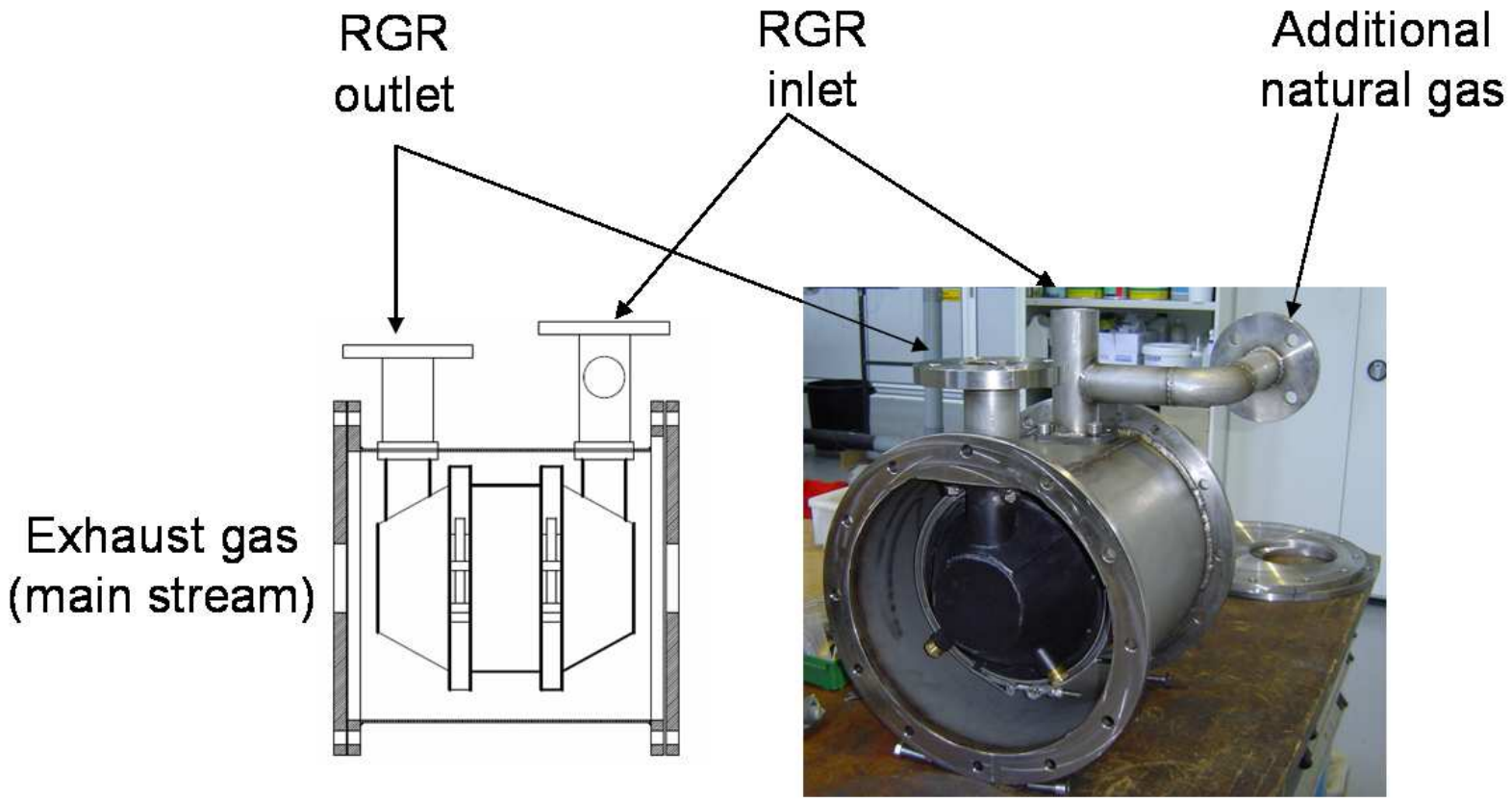

RGR
outlet
RGR
inlet
Additional
natural gas
Exhaust gas
(main stream)

Figure 3

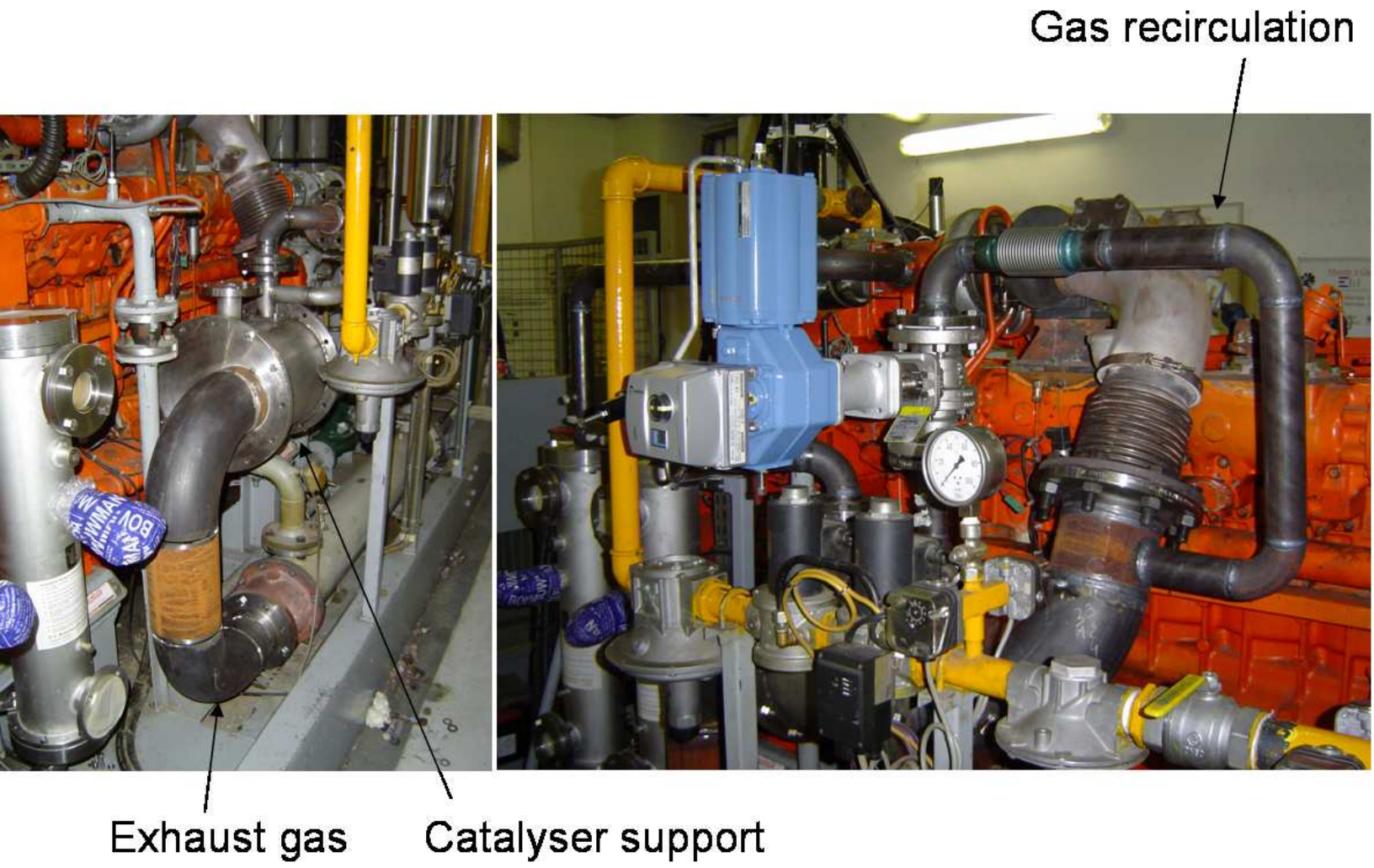


Figure 4

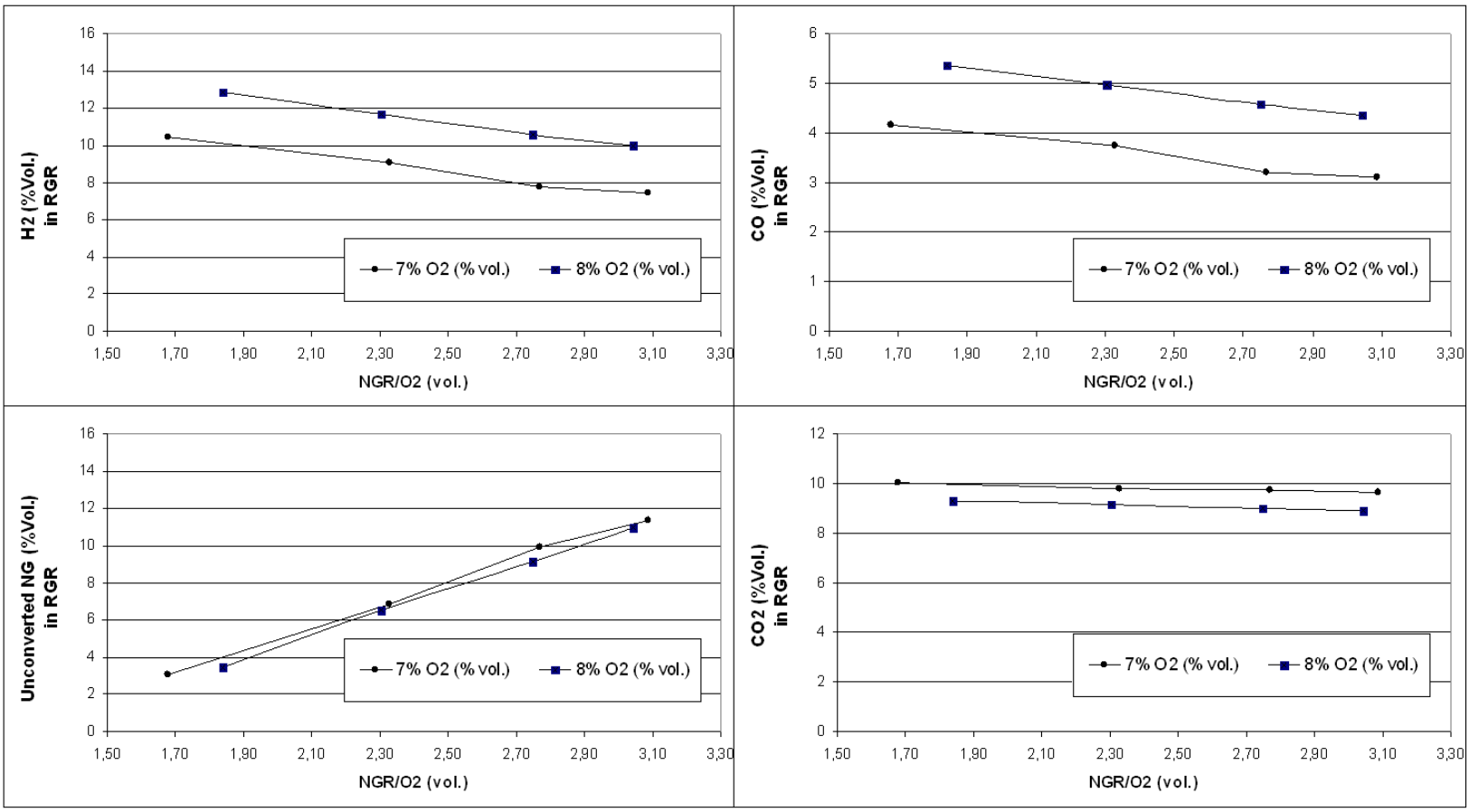
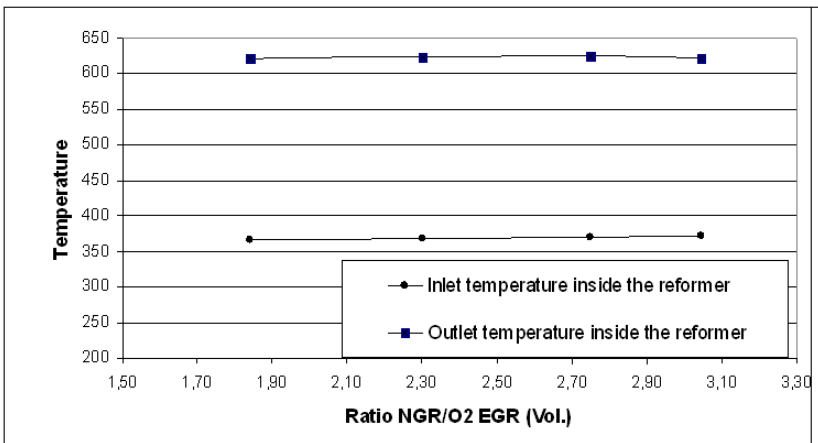
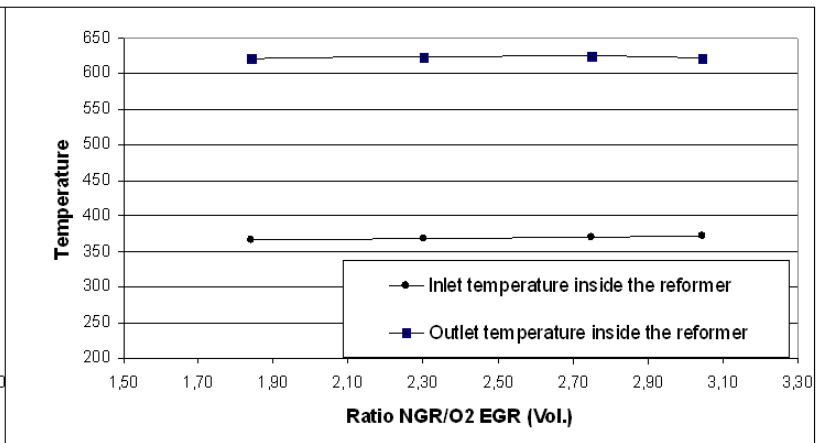
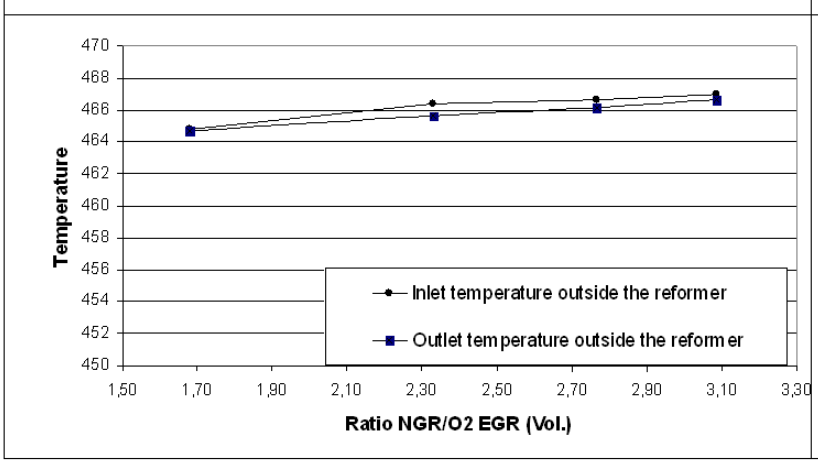

H2 (%Vol.) in RGR
CO (%Vol.) in RGR
Unconverted NG (%Vol.) in RGR
CO2 (%Vol.) in RGR
NGR/O2 (vol.)
7% O2 (% vol.)
8% O2 (% vol.)
1,50
1,70
1,90
2,10
2,30
2,50
2,70
2,90
3,10
3,30

Figure 5


650
600
550
500
450
400
350
300
250
200
Temperature
1,50
1,70
1,90
2,10
2,30
2,50
2,70
2,90
3,10
3,30
Ratio NGR/O2 EGR (Vol.)
Inlet temperature inside the reformer
Outlet temperature inside the reformer


650
600
550
500
450
400
350
300
250
200
Temperature
1,50
1,70
1,90
2,10
2,30
2,50
2,70
2,90
3,10
3,30
Ratio NGR/O2 EGR (Vol.)
Inlet temperature inside the reformer
Outlet temperature inside the reformer


470
468
466
464
462
460
458
456
454
452
450
Temperature
1,50
1,70
1,90
2,10
2,30
2,50
2,70
2,90
3,10
3,30
Ratio NGR/O2 EGR (Vol.)
Inlet temperature outside the reformer
Outlet temperature outside the reformer

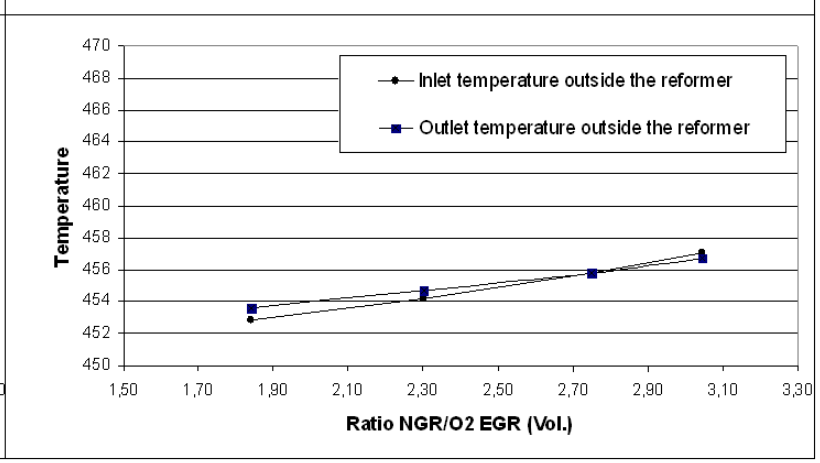

470
468
466
464
462
460
458
456
454
452
450
Temperature
1,50
1,70
1,90
2,10
2,30
2,50
2,70
2,90
3,10
3,30
Ratio NGR/O2 EGR (Vol.)
Inlet temperature outside the reformer
Outlet temperature outside the reformer

Figure 6

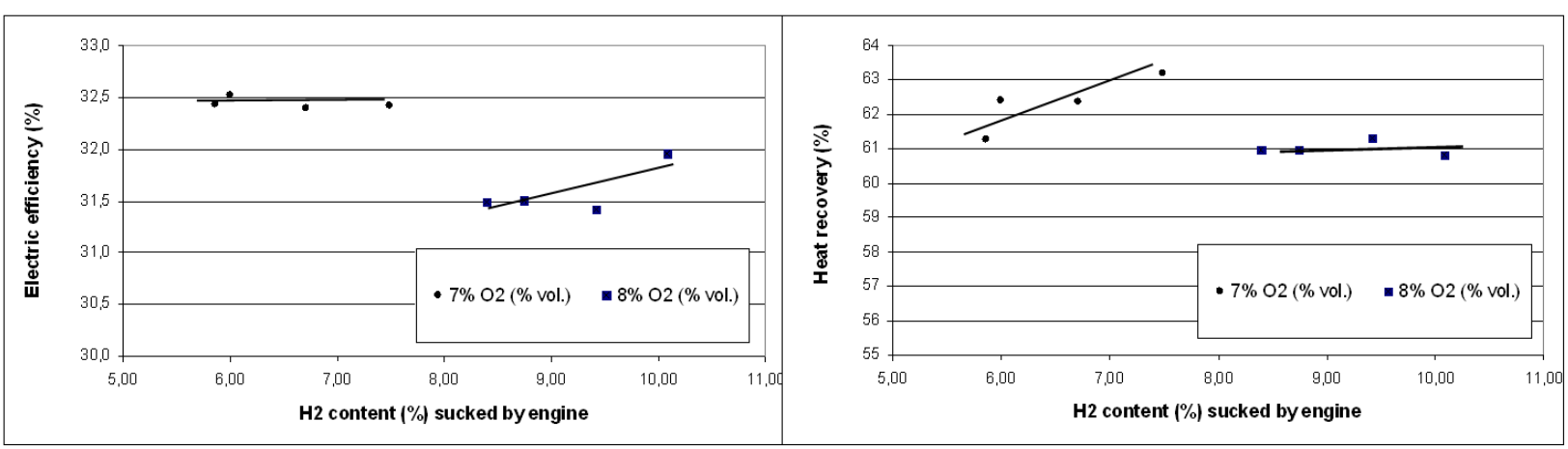
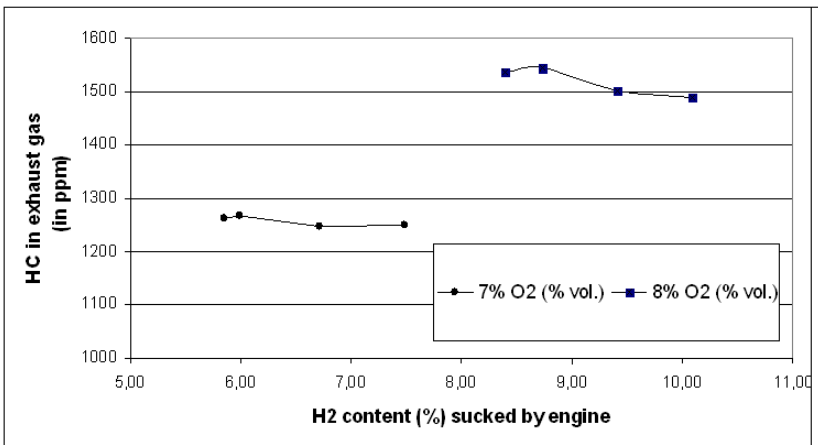
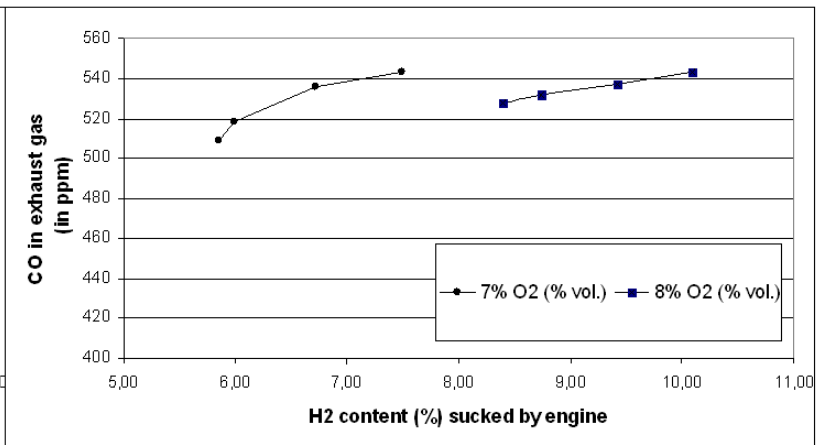
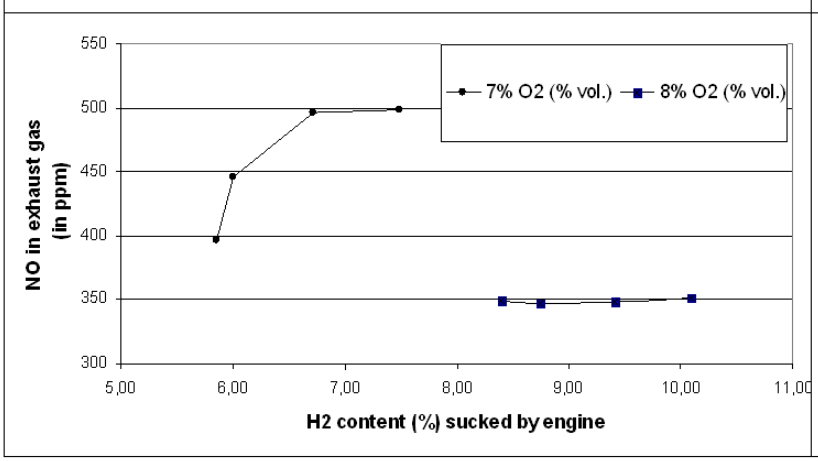

Electric efficiency (%)
33,0
32,5
32,0
31,5
31,0
30,5
30,0
5,00
6,00
7,00
8,00
9,00
10,00
11,00
H2 content (%) sucked by engine
7% O2 (% vol.)
8% O2 (% vol.)
Heat recovery (%)
64
63
62
61
60
59
58
57
56
55
5,00
6,00
7,00
8,00
9,00
10,00
11,00
H2 content (%) sucked by engine
7% O2 (% vol.)
8% O2 (% vol.)

Figure 7


HC in exhaust gas (in ppm)
1600
1500
1400
1300
1200
1100
1000
5,00
6,00
7,00
8,00
9,00
10,00
11,00
H2 content (%) sucked by engine
7% O2 (% vol.)
8% O2 (% vol.)


CO in exhaust gas (in ppm)
560
540
520
500
480
460
440
420
400
5,00
6,00
7,00
8,00
9,00
10,00
11,00
H2 content (%) sucked by engine
7% O2 (% vol.)
8% O2 (% vol.)


NO in exhaust gas (in ppm)
550
500
450
400
350
300
5,00
6,00
7,00
8,00
9,00
10,00
11,00
H2 content (%) sucked by engine
7% O2 (% vol.)
8% O2 (% vol.)

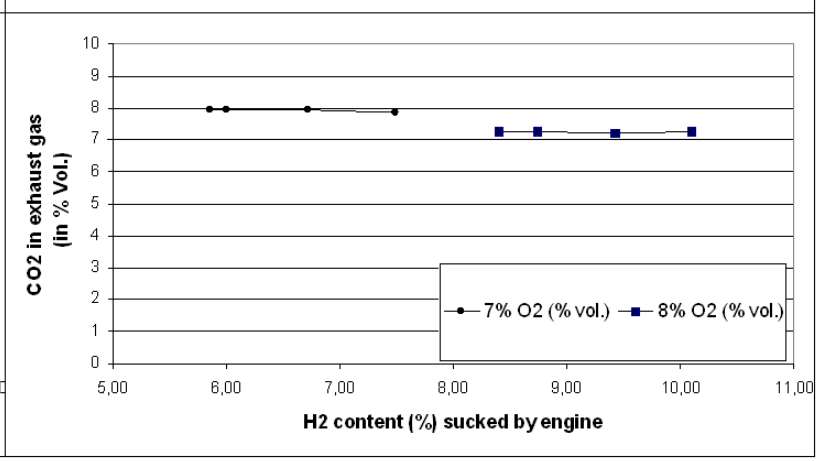

CO2 in exhaust gas (in % Vol.)
10
9
8
7
6
5
4
3
2
1
0
5,00
6,00
7,00
8,00
9,00
10,00
11,00
H2 content (%) sucked by engine
7% O2 (% vol.)
8% O2 (% vol.)

Figure 8

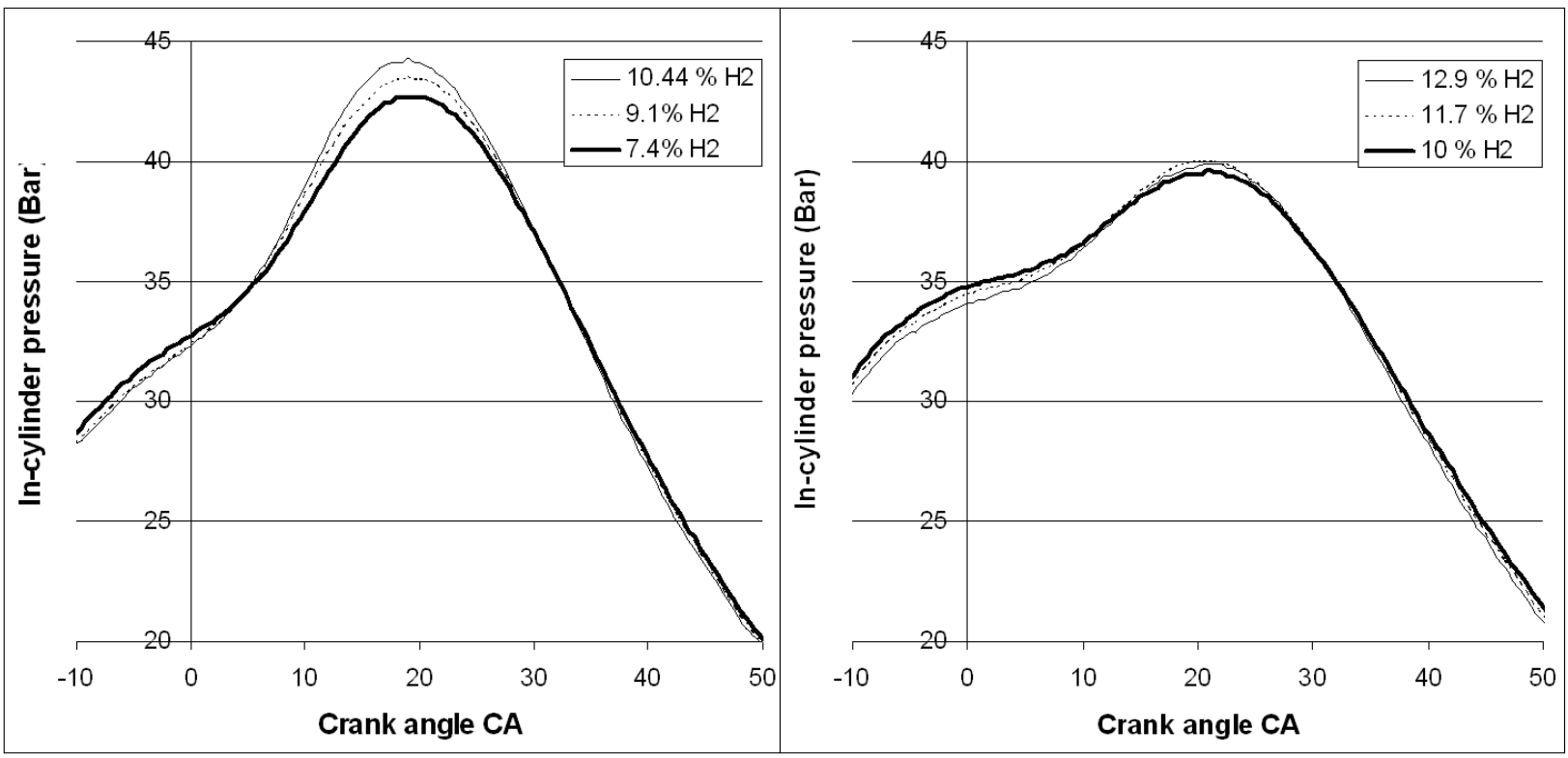

45
40
35
30
25
20
-10
0
10
20
30
40
50
In-cylinder pressure (Bar)
Crank angle CA
10.44 % H2
9.1% H2
7.4% H2
12.9 % H2
11.7 % H2
10 % H2

Figure 9

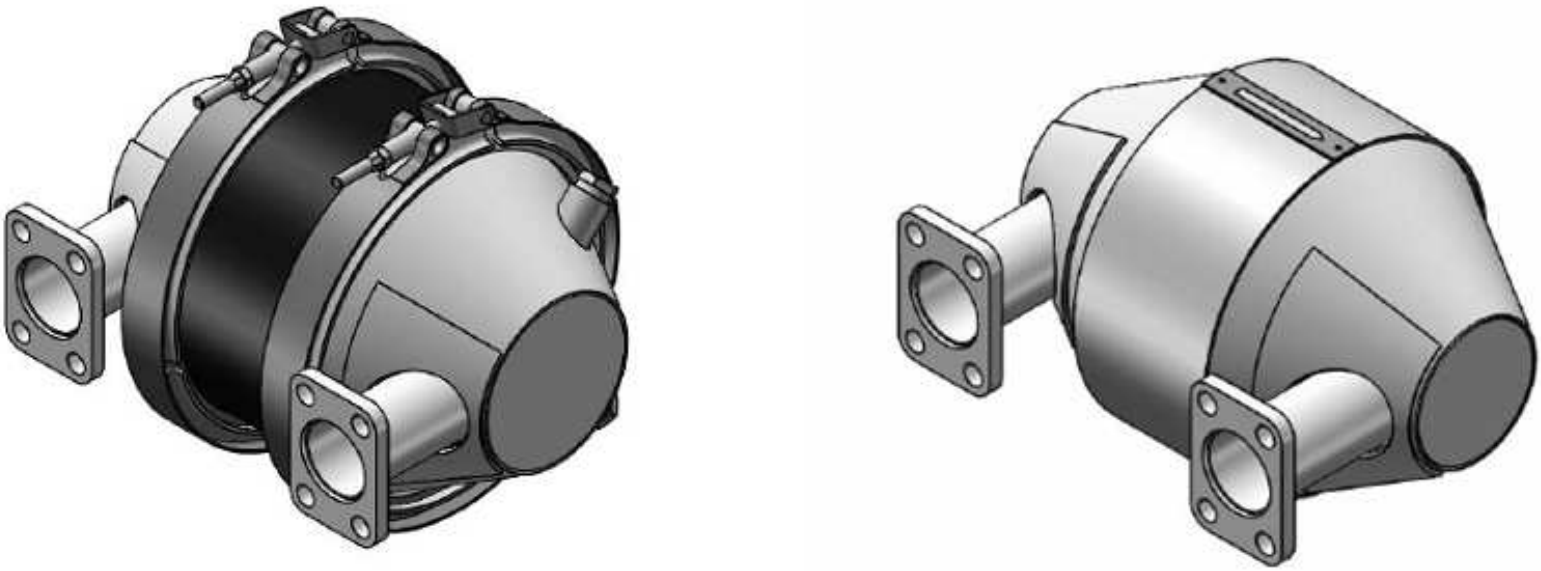


Figure 10

Table 1

Table 1: Review of fuel-H_2 blends fuelled in SI engine.

Reference	Nagalingam *et al.* [5]	Collier *et al.* [6] Hoekstra *et al.* [7]	Apolescu and Chiriac [8]	Bade and Karim [9]	Bauer [10] Bauer and Forest [4]	Al-Baghadi and Al-Janabi [11, 12]	Raman *et al.* [13]	Swain *et al.* [14]	Cattelan and Wallace [15]	Collier *et al.* [6] Hoeskstra *et al.* [7]	Vandenborre and Sierens [16], Verhelst and Sierens [17, 18]	Munshi *et al.* [19]	Collier *et al.* [20]
	523.001	C.F.R.	Dacia	Waukesha CFR	C.F.R.	E6/US CFR	G.M.	Nissan / Toyota	Chevrolet	V8	Crusader T7400 GM 454	A.V.L.	Daewoo
Fuel	NG - H_2												
Number of cylinders	1	1	1	1	1	1	8	4 / 4	4	8	8 V	6	6
Bore (mm)	125	82.55	73	82.5		76.2		85 / 85	89	90.2	107.95	102	
Stroke (mm)	130	92.08	77	114.3		110	86 / 70	84	90	101.6	120		
Displaced volume (cm^3)	1595	492.8	322	612	610		5700	1981 / 1588	2100	4600	7410	5 900	11 000
Compression ratio	11	14.04	8.5	4-18	8.5	Variable		9 / 8.8	8.8	8.5	9	10.5	
Speed (rev/min)	fixed	1700	1800			1500	2500			1700	3800	var.	
Spark Ignition (CA)	variable			fixed 20CA		var.	B.E.S.T						
Efficiency				high efficiency		Greater / pure fuel		↗			Benefit 1 point absolute		Benefit 1 point absolute
NOx	↗	↗	↘	↘	+30 %	Lower / pure fuel		↗		↗	Divided by 4 on NO_x	↘50 %	0.1 g/kWh
HC	↘	↘	↗	↘	-50 %			↘	↘	↘		↘58 %	2 g/kWh
CO	↘	↘		↘	Near null			↘	↘	↘		Weak decreasing	1.5 g/kWh
CO_2		↘		↘	-26 %			↘	↘	↘			
Comments	Power ↘ modif. SA	Obj: E.Z.E.V.		Power ↗	Specific fuel consumption - 14 %	Operating conditions $\phi = 0.4 - 0.6$	hyperbole HC/NO_x			Obj. E.Z.E.V.			

Table 2

Table 2: Engine specifications.

Engine manufacturer	GUASCOR FGLD 180	
Cylinder number	6	
Bore	152	mm
Stroke	165	mm
Displaced volume by cylinder/ total	2 994 / 17 964	cm^3
Clearance volume	300	cm^3
Compression ratio	11:1	
Number of suction valve/exhaust valve	2 / 2 per cylinder	
Valve train : IO/IC/EO/EC	25 ATDC/ 45 ABDC/ 60 BBDC/ 15 BTDC	CA
Turbo-charger	1.8 BAR	
Engine speed	1 500	RPM
Ignition Timing	14 BTDC	

ATDC: after top dead center; BBDC: before bottom dead center; ABDC: after bottom dead center; BTDC: before top dead center.

Table 3

Table 3: Comparison of EGR-RGR results.

	Electric efficiency	Heat recovery	CO (exhaust gas)	NO (exhaust gas)	HC (exhaust gas)
EGR 5%	32.9%	60.7%	505 ppm	378 ppm	1223 ppm
RGR 5%	33.2%	59.7%	578 ppm	310 ppm	1070 ppm